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“Vibrations – Ways out of the annoyance”
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Stiff wave barriers for the mitigation of railway induced vibrations

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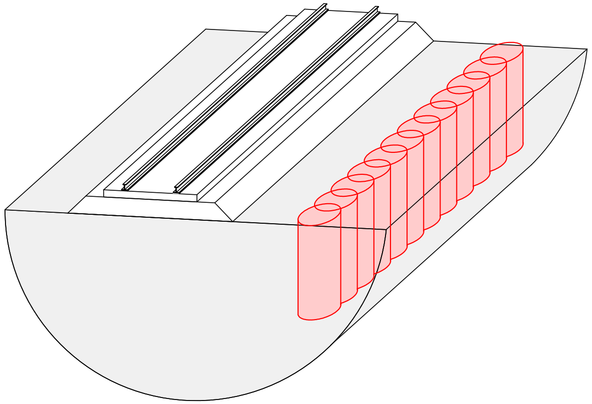
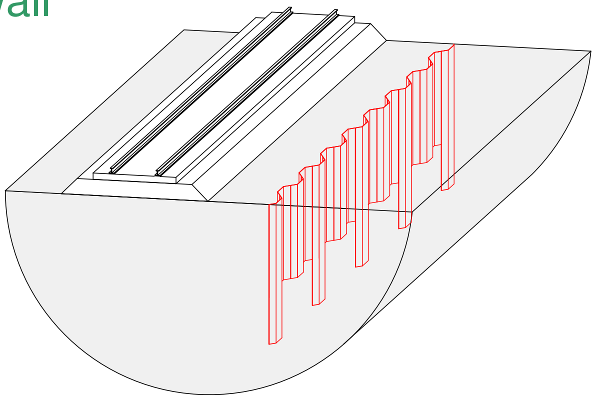
Introduction

Stiff wave barriers

- Two types of stiff wave barriers are considered in this presentation:
  - Jet grouting wall



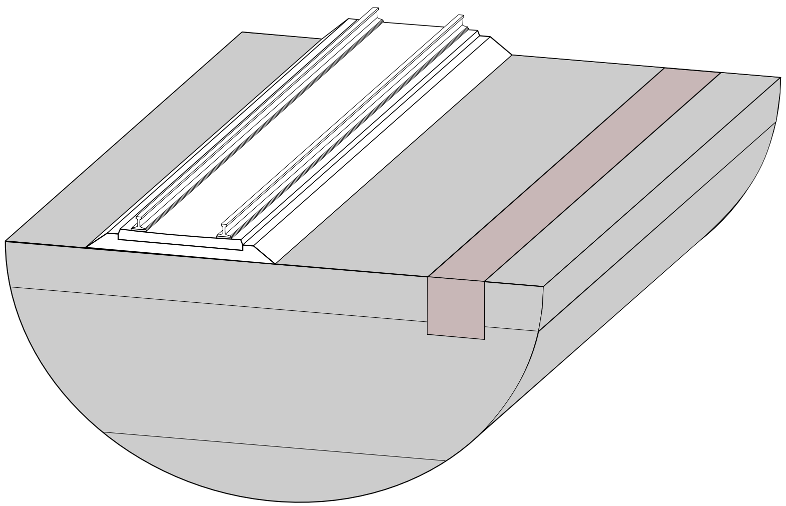
  - Sheet piling wall

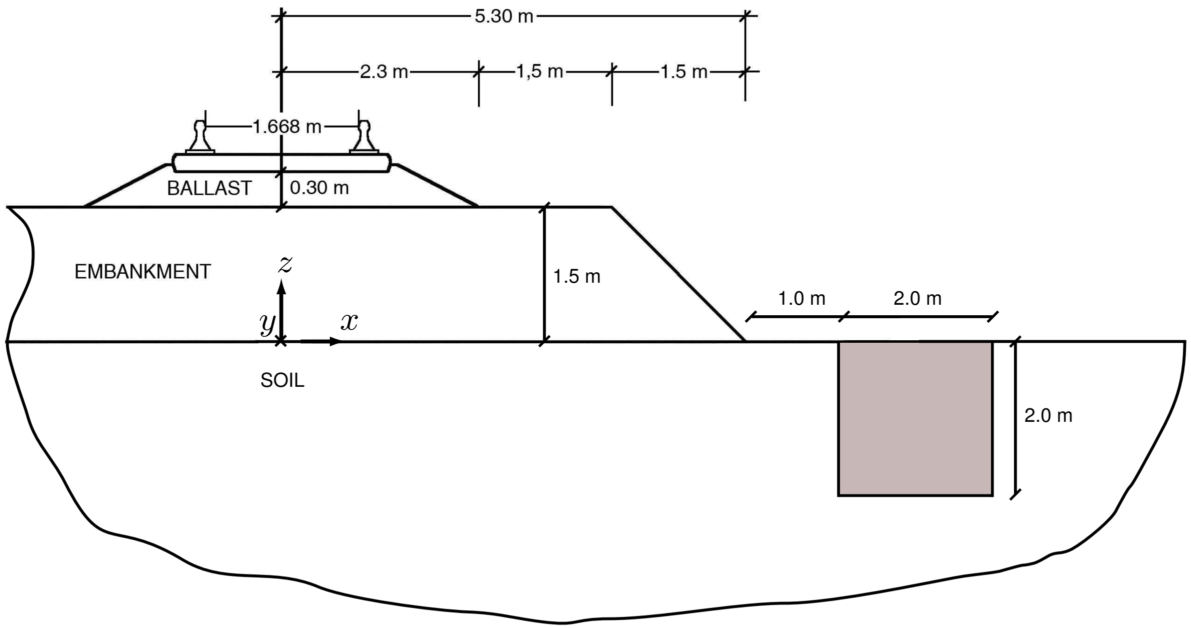


Jet grouting wall

Stiff wave barrier next to the track

- Jet grouting wall ($w = h = 2\,\mathrm{m}$) in a homogeneous halfspace



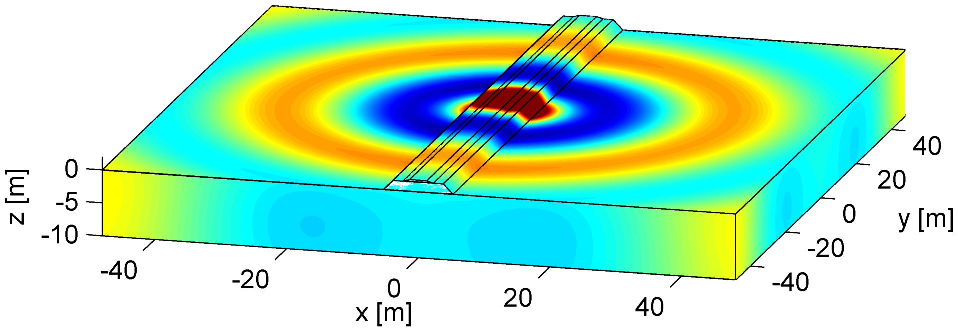


	C_s $[\mathrm{m/s}]$	C_p $[\mathrm{m/s}]$	β_s $[-]$	β_p $[-]$	ρ $[\mathrm{kg/m^3}]$
Halfspace	200	400	0.025	0.025	2000
Stiffened soil	550	950	0.05	0.05	2000

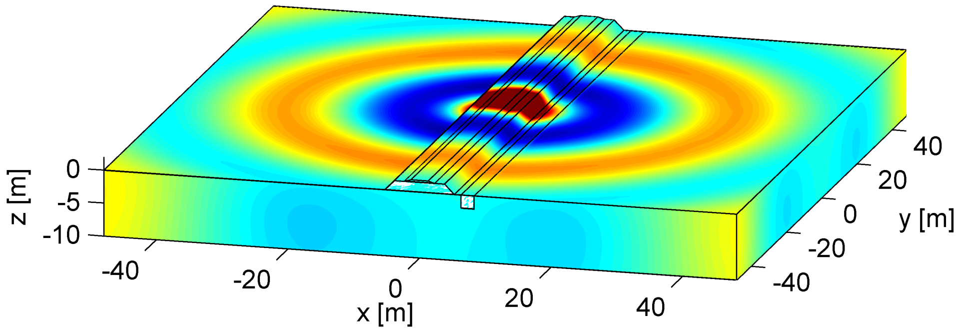
Transfer functions

- Real part of the vertical displacement field $\hat{u}_z(\mathbf{x}, \omega)$ at $5\,\mathrm{Hz}$

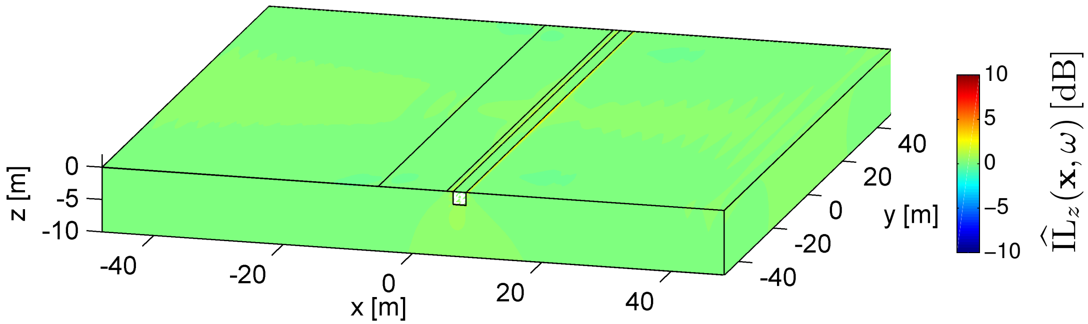
without barrier



with barrier



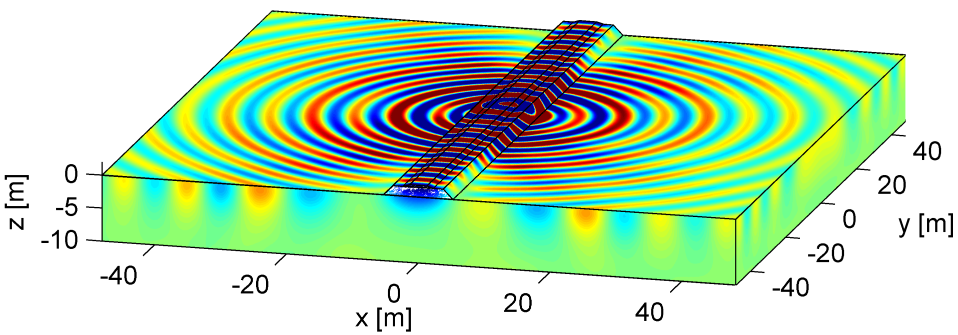
- Corresponding insertion loss $\widehat{\mathrm{IL}}_z(\mathbf{x}, \omega) = 20\log_{10}\frac{|\hat{u}_z^{\mathrm{ref}}(\mathbf{x},\omega)|}{|\hat{u}_z(\mathbf{x},\omega)|}$



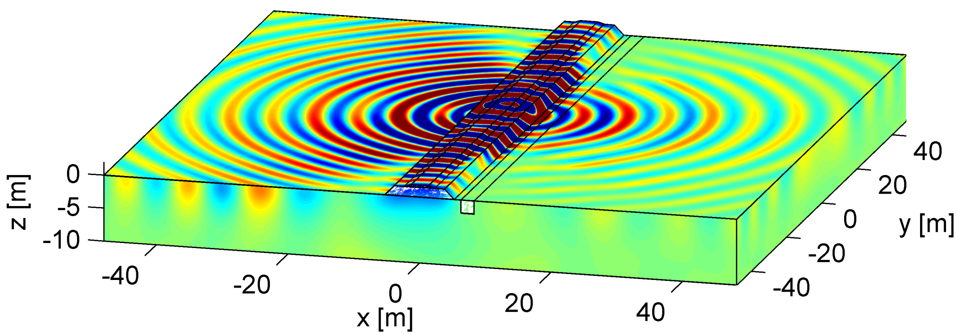
Transfer functions

- Real part of the vertical displacement field $\hat{u}_z(\mathbf{x}, \omega)$ at $30\,\mathrm{Hz}$

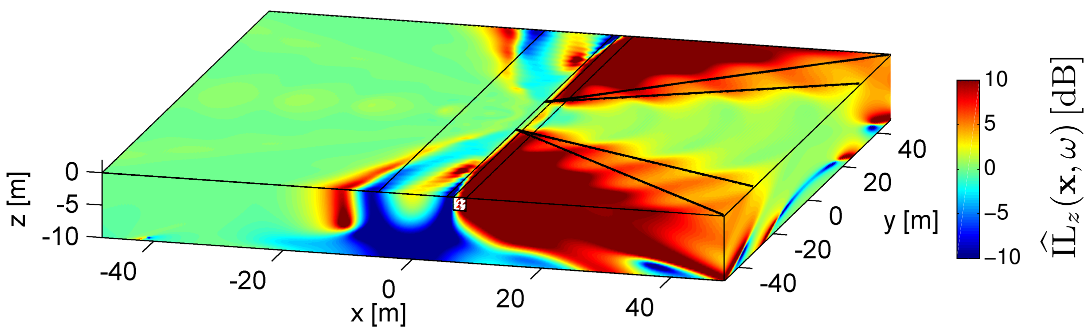
without barrier



with barrier



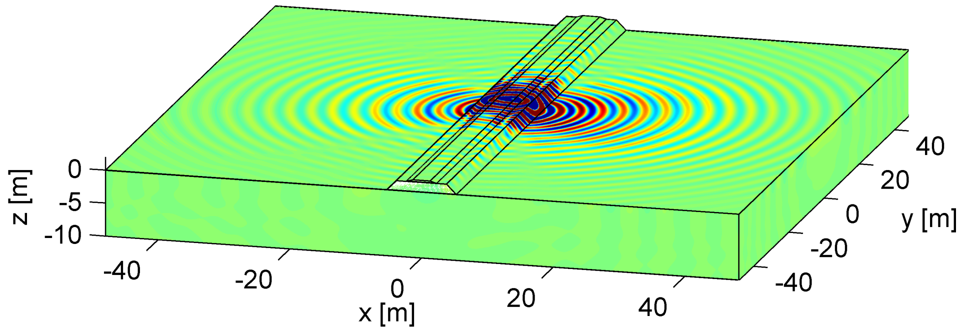
- Corresponding insertion loss $\widehat{\mathrm{IL}}_z(\mathbf{x}, \omega) = 20\log_{10} \frac{|\hat{u}_z^{\mathrm{ref}}(\mathbf{x},\omega)|}{|\hat{u}_z(\mathbf{x},\omega)|}$



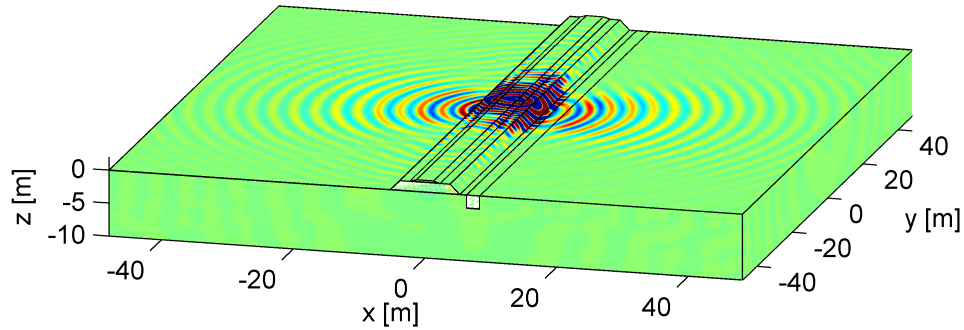
Transfer functions

- Real part of the vertical displacement field $\hat{u}_z(\mathbf{x},\omega)$ at $60\,\mathrm{Hz}$

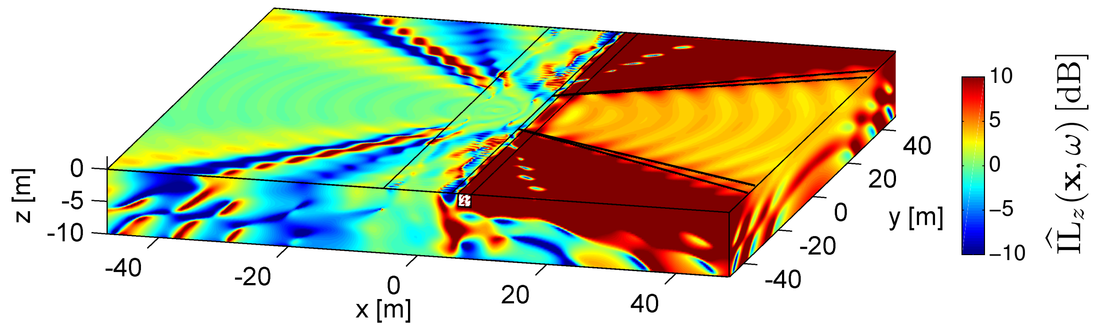
without barrier



with barrier



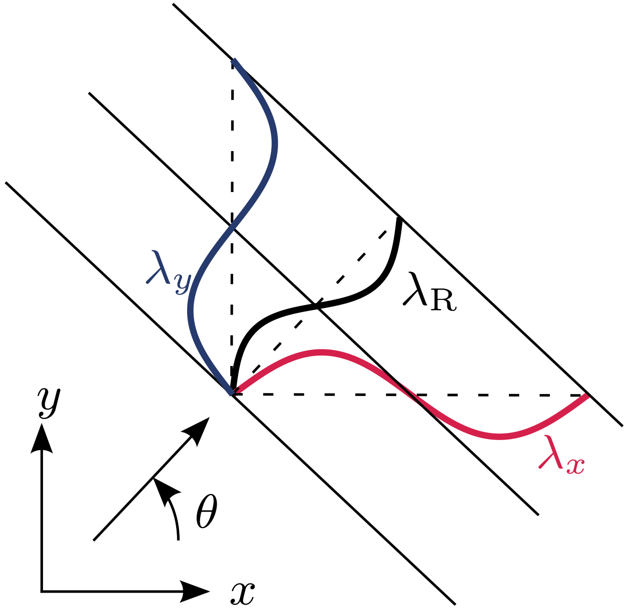
- Corresponding insertion loss $\widehat{\mathrm{IL}}_z(\mathbf{x},\omega) = 20\log_{10}\frac{|\hat{u}_z^{\mathrm{ref}}(\mathbf{x},\omega)|}{|\hat{u}_z(\mathbf{x},\omega)|}$

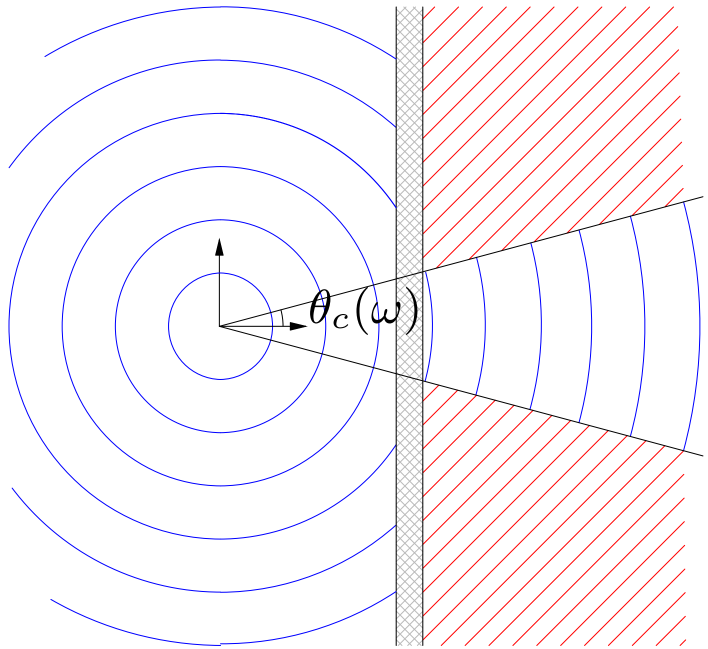


Transfer functions

Interaction of Rayleigh waves in the soil and bending waves in the stiff wave barrier

- Cylindrical wavefield can be decomposed into plane waves, satisfying the dispersion relation $\frac{1}{\lambda_x^2} + \frac{1}{\lambda_y^2} = \frac{1}{\lambda_R^2}$, where $\lambda_R = 2\pi \frac{C_R}{\omega}$ is the Rayleigh wavelength.

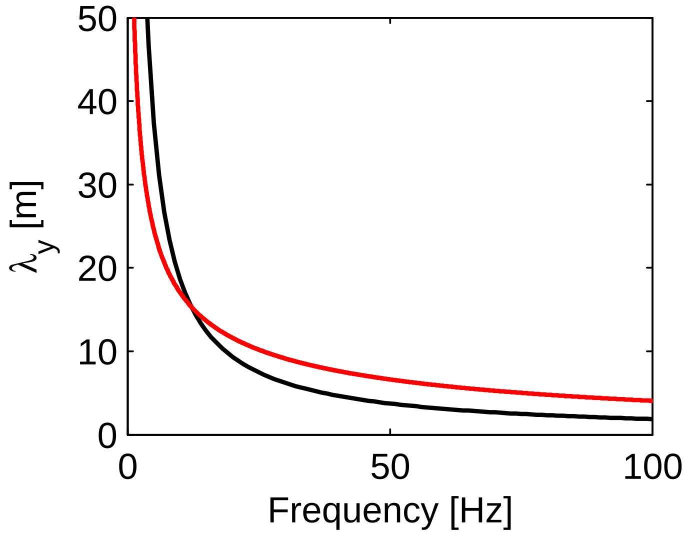




- Propagating plane waves are characterized by $\lambda_R \leqslant \lambda_y \leqslant \infty$:
  - $\theta = 0 \Rightarrow \lambda_x = \lambda_R, \lambda_y = \infty$
  - $\theta = \pi/2 \Rightarrow \lambda_y = \lambda_R, \lambda_x = \infty$

Transfer functions

Interaction of Rayleigh waves in the soil and bending waves in the stiff wave barrier



- Rayleigh wave dispersion curve (black line):

$$\lambda_{\mathrm{R}} = 2\pi \frac{C_{\mathrm{R}}}{\omega}$$

- Free bending wave dispersion curve (red line):

$$\lambda_{\mathrm{b}} = \frac{2\pi}{\sqrt{\omega}} \left(\frac{EI}{\rho A} \right)^{1/4}$$

- $f < f_{\mathrm{c}}$: $\lambda_{\mathrm{b}} < \lambda_{\mathrm{R}} \Rightarrow$ Rayleigh waves propagate unhindered through the block of stiffened soil
- $f > f_{\mathrm{c}}$: $\lambda_{\mathrm{b}} > \lambda_{\mathrm{R}} \Rightarrow$ wavefield is partially transmitted, partially blocked
  - $\lambda_y > \lambda_{\mathrm{b}}$: plane waves are transmitted
  - $\lambda_y < \lambda_{\mathrm{b}}$: transmission of plane waves is impeded by the block of stiffened soil

- Critical frequency f_{c}:

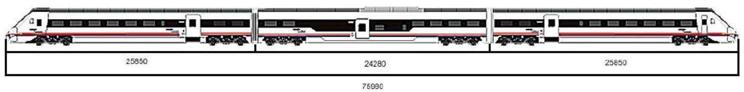
$$f_{\mathrm{c}} = \frac{C_{\mathrm{R}}^2}{2\pi h} \sqrt{\frac{12\rho}{E}} = 12\,\mathrm{Hz}$$

- Critical angle $\theta_{\mathrm{c}}(\omega) = \sin^{-1}\left(\lambda_{\mathrm{R}}/\lambda_{\mathrm{b}}\right)$:

$$\sin\theta_{\mathrm{c}}(\omega) = \frac{C_{\mathrm{R}}}{\sqrt{\omega h}} \left(\frac{12\rho}{E} \right)^{1/4}$$

Train passage

Passage of a Renfe S599 train at $160\,\mathrm{km/h}$



- Simplified model: only the unsprung masses are taken into account

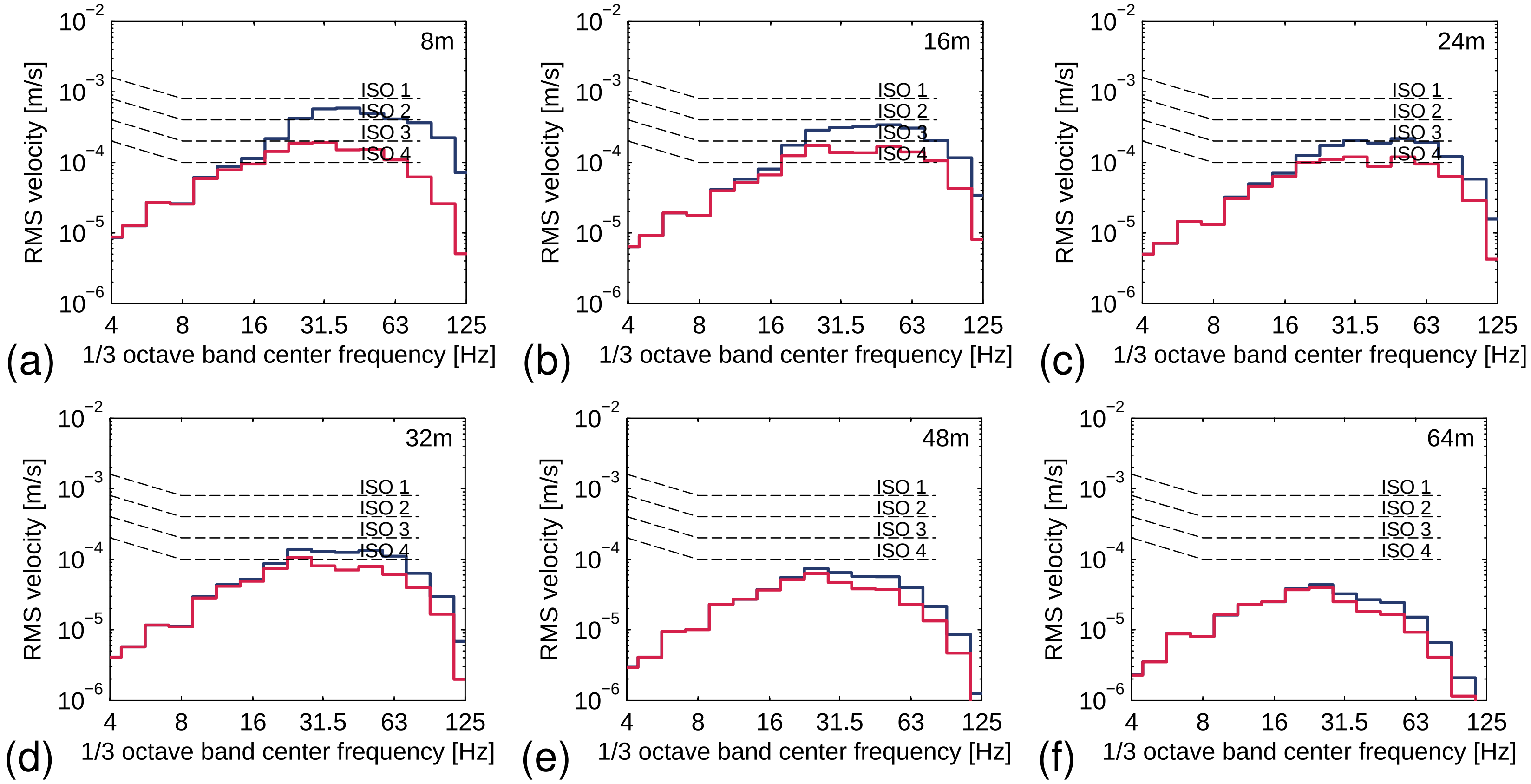
	N_{a} [−]	L_{t} [m]	L_{b} [m]	L_{a} [m]	M_{u} [kg]
Two motor coaches	4	25.85	17.73	2.50	1940
One central carriage	4	24.28	18.00	2.50	1704

- Hertzian contact spring ($k_{\mathrm{Hz}} = 3 \times 10^9\,\mathrm{N/m}$); FRA track unevenness (class 3)

Train passage

Passage of a Renfe S599 train at $160\,\mathrm{km/h}$

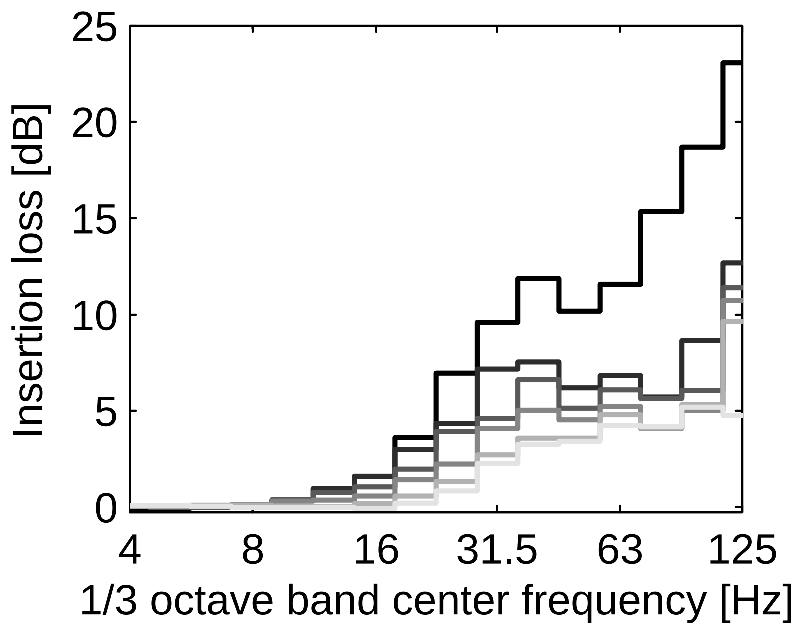
- One–third octave band RMS spectra of the vertical free field vibrations in the reference case (blue lines) and in case of stiffening next to the track (red lines)
- In case of subgrade stiffening next to the track, a reduction of vibration levels is obtained from the critical frequency of $12\,\mathrm{Hz}$ on.



Train passage

Passage of a Renfe S599 train at $160\,\mathrm{km/h}$

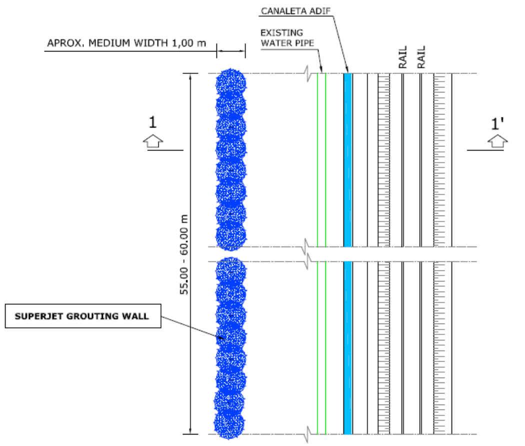
- Vertical insertion loss $\widehat{\mathrm{IL}}_z(\mathbf{x}, \omega)$ at $8\,\mathrm{m}$, $16\,\mathrm{m}$, $24\,\mathrm{m}$, $32\,\mathrm{m}$, $48\,\mathrm{m}$ and $64\,\mathrm{m}$ from the center of the track (black to light grey lines) due to the passage of a Renfe S599 at a speed of $160\,\mathrm{km/h}$:
  - $\widehat{\mathrm{IL}}_z(x_1, \bar{\omega}) > \widehat{\mathrm{IL}}_z(x_2, \bar{\omega})$ with $x_1 < x_2$
  - $\widehat{\mathrm{IL}}_z(\bar{x}, \omega_1) < \widehat{\mathrm{IL}}_z(\bar{x}, \omega_2)$ with $\omega_1 < \omega_2$



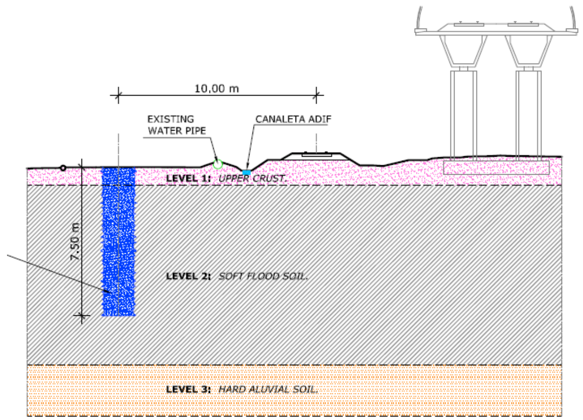
Test site

El Realengo test site

- El Realengo test site in Spain: low Segura river flood plain.
- Conventional railway line (ADIF) between Murcia and Alicante
- A jet grouting wall of $1\,\mathrm{m} \times 55\,\mathrm{m} \times 7.5\,\mathrm{m}$ has been constructed



SUPERJET GROUTING WALL LAYOUT



SECCIÓN 1-1'.

- An extensive measurement campaign will be carried out to verify the effectiveness of the jet grouting wall

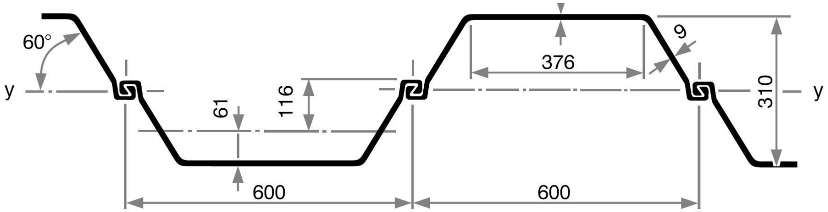
Sheet piling wall

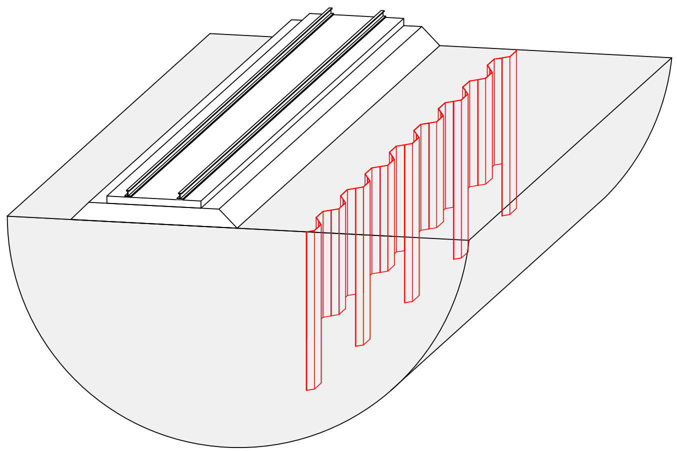
Furet

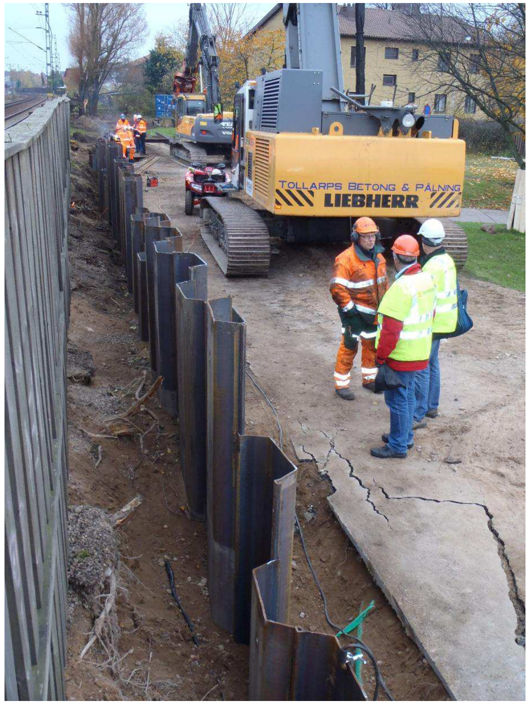
- Located in southwest of Sweden along the West Coast Line between Gothenburg and Lund
- Vibration problems in houses nearby ($4 - 5\,\mathrm{Hz}$)

Sheet piling wall ($100\,\mathrm{m}$)

- VL 603-K profiles with depth of $12\,\mathrm{m}$, every fourth pile extended to $18\,\mathrm{m}$



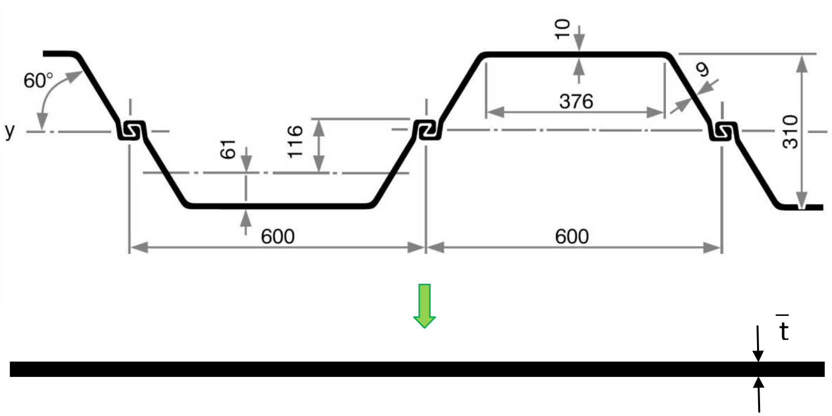


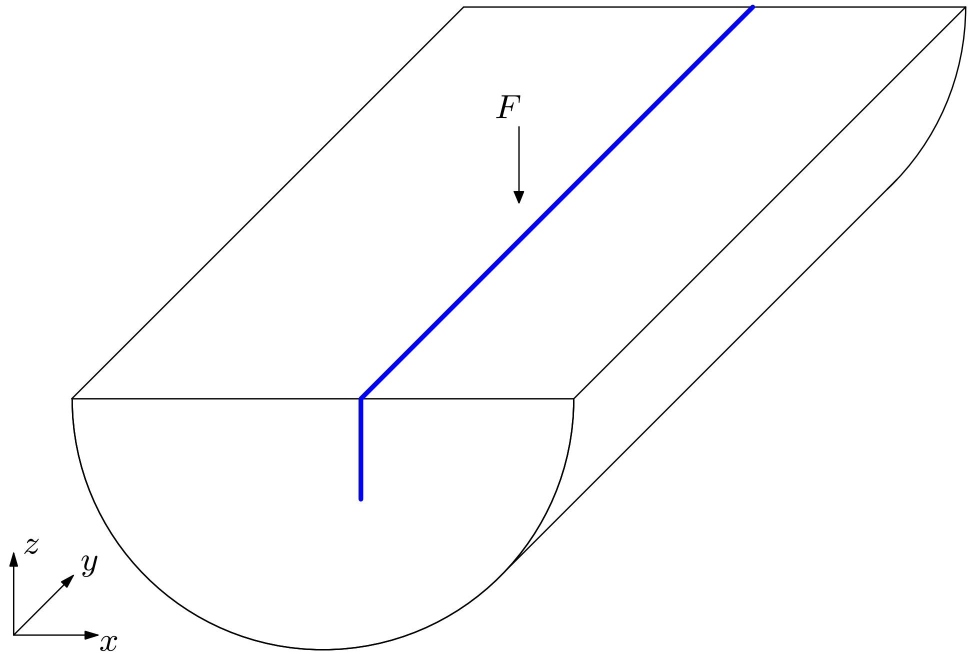


Sheet piling wall model

2.5D methodology

- Longitudinally invariant geometry
  - Two models: depth $12\,\mathrm{m}$ and $18\,\mathrm{m}$
  - Profiling





Equivalent orthotropic plate model

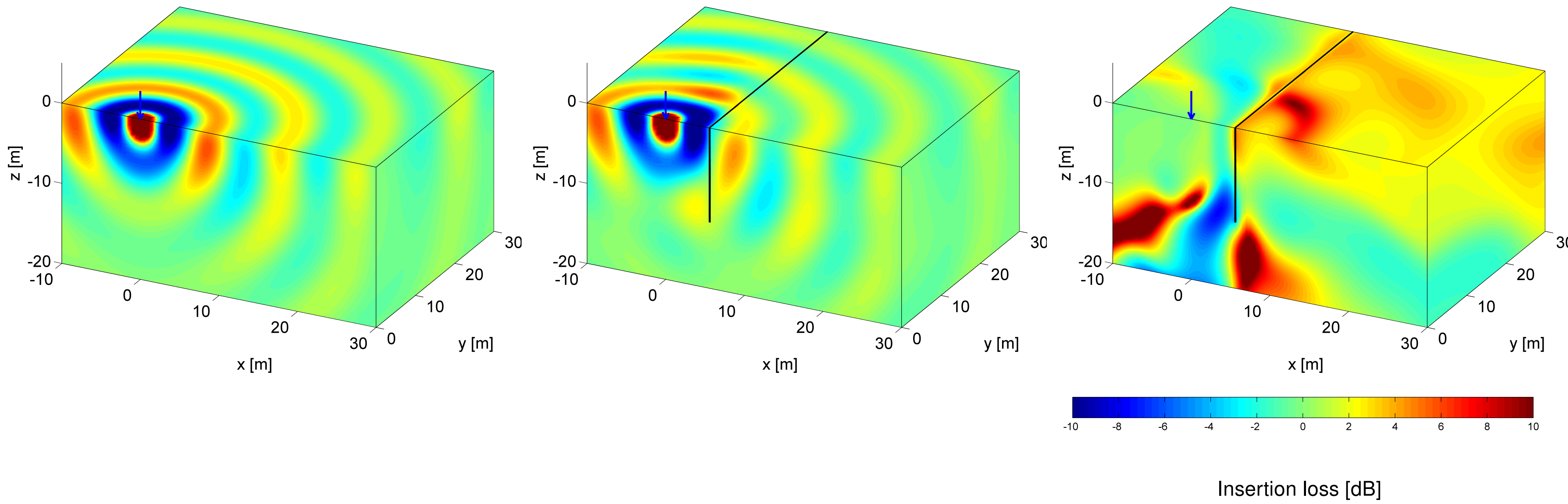
- Bending stiffness along the profiles B_z is much larger than bending stiffness perpendicular to the profiles B_y

Homogeneous halfspace

Dynamic soil characteristics (Horstwalde)

Layer	C_{s} $[\mathrm{m/s}]$	C_{p} $[\mathrm{m/s}]$	β_{s} $[-]$	β_{p} $[-]$	ρ $[\mathrm{kg/m^3}]$	ν $[-]$
Halfspace	250	1470	0.025	0.025	1945	0.485

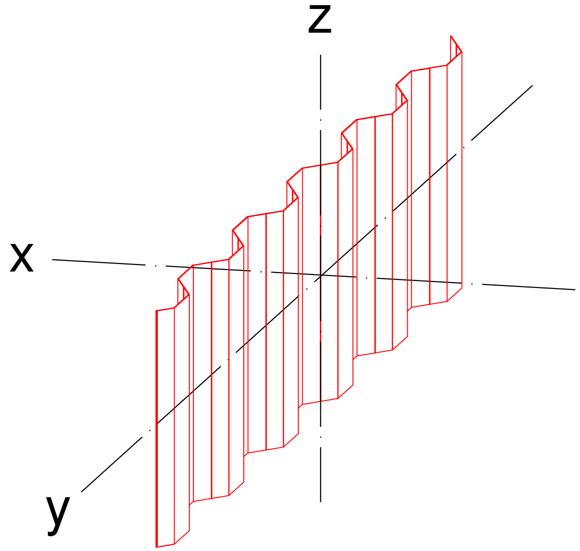
Vertical displacement and corresponding IL at $25\,\mathrm{Hz}$



Homogeneous halfspace

Wave impeding effect due to longitudinal bending stiffness

- Longitudinal bending waves with bending around x-axis are not excited due to limited width
- Longitudinal bending waves with bending around z-axis do not play a role due to low bending stiffness



Homogeneous halfspace

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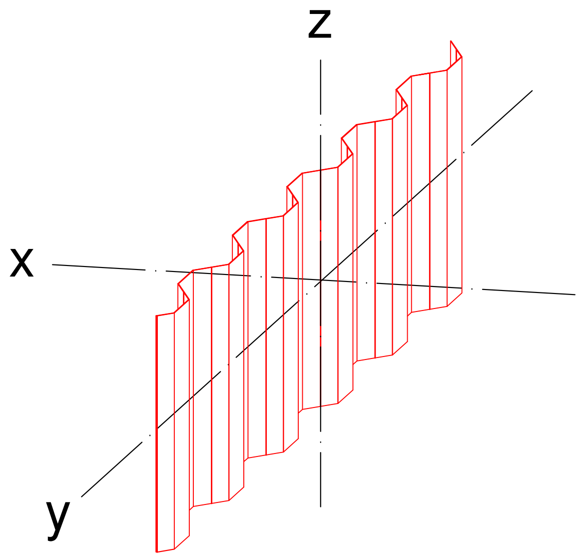


Wave impeding effect due to reflection of Rayleigh waves

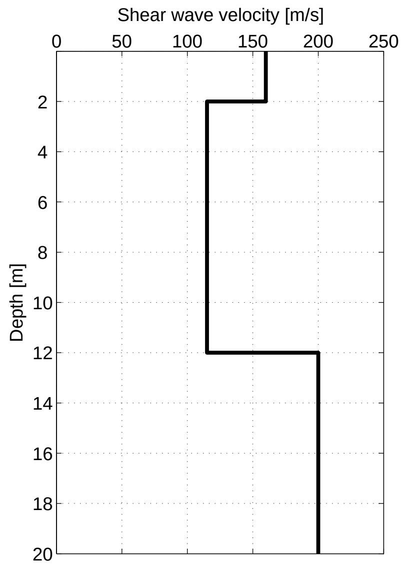
- When the depth of the wave barrier is large enough compared to the Rayleigh wave length
- Rule of thumb: $d > 0.75\lambda_{\mathrm{R}}$
- Almost independent of angle of incidence

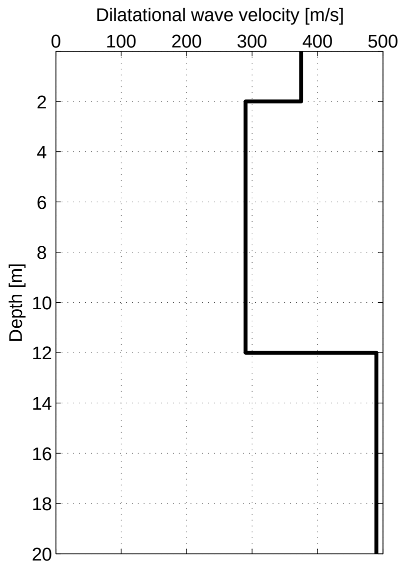
Furet test site

Dynamic soil characteristics

- Geotechnical and geophysical surveys
- Soil profile

Layer	h [m]	C_{s} [m/s]	C_{p} [m/s]	β_{s} [−]	β_{p} [−]	ρ [kg/m^3]	ν [−]
1	2.0	154	375	0.025	0.025	1800	0.40
2	10.0	119	290	0.025	0.025	1850	0.40
Halfspace	∞	200	490	0.025	0.025	1710	0.40

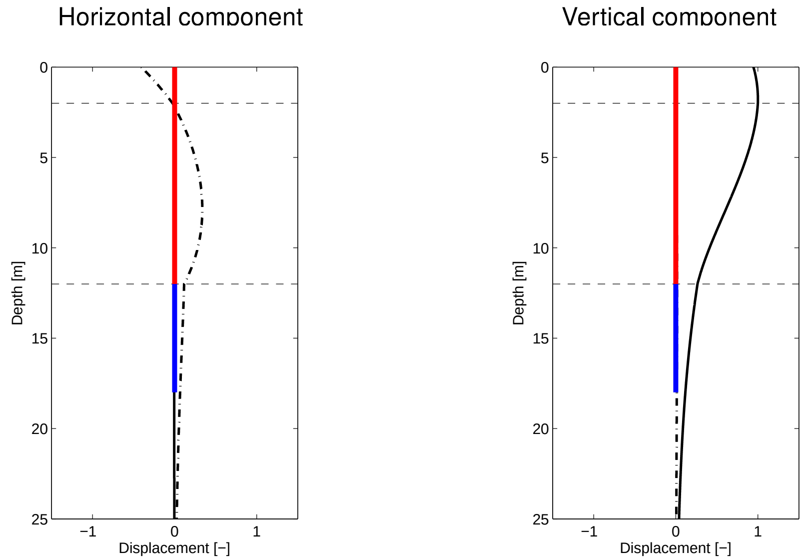




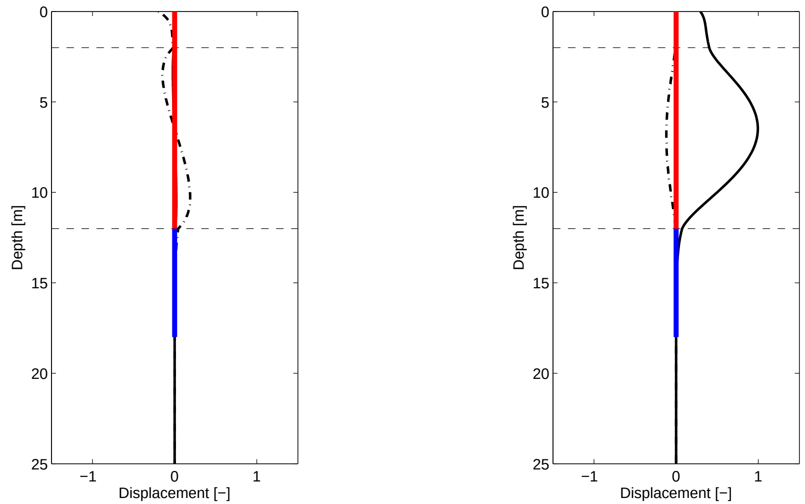
Furet test site

Fundamental Rayleigh wave

- Real (solid line) and imaginary (dashed-dotted line) part of the fundamental Rayleigh wave at $5\,\mathrm{Hz}$

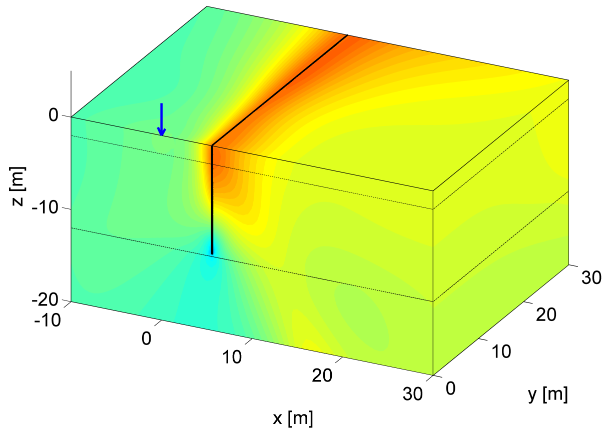


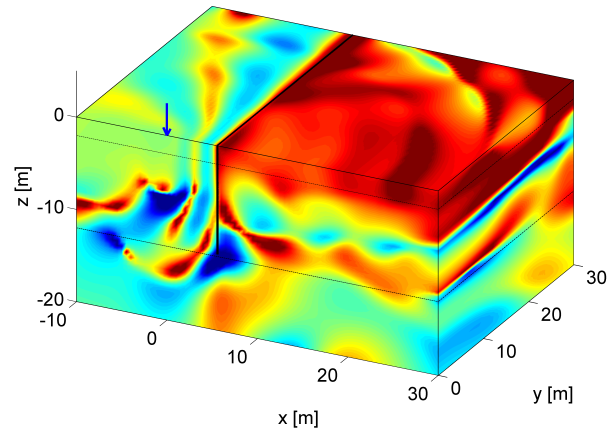
- Real (solid line) and imaginary (dashed-dotted line) part of the fundamental Rayleigh wave at $25\,\mathrm{Hz}$



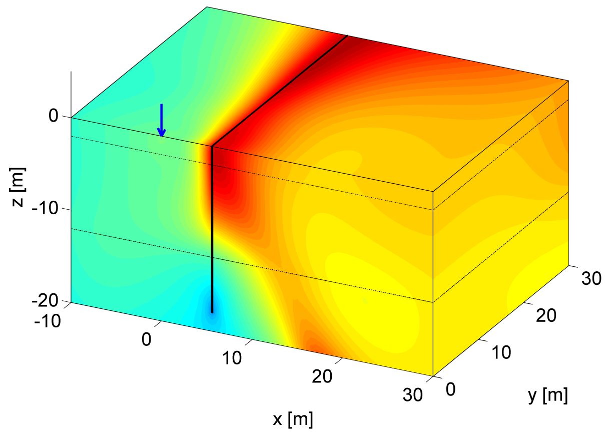
Furet test site

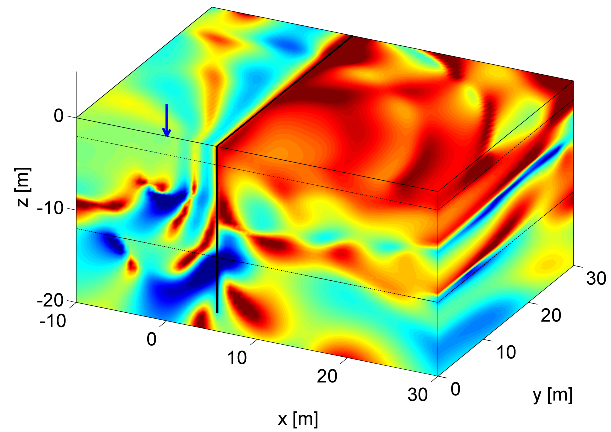
- Vertical insertion loss for a $12\,\mathrm{m}$ deep sheet pile wall at $5\,\mathrm{Hz}$ (left) and $25\,\mathrm{Hz}$ (right)

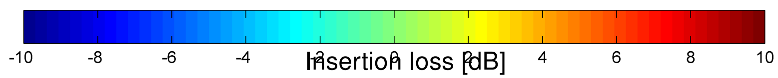




- Vertical insertion loss for a $18\,\mathrm{m}$ deep sheet pile wall at $5\,\mathrm{Hz}$ (left) and $25\,\mathrm{Hz}$ (right)

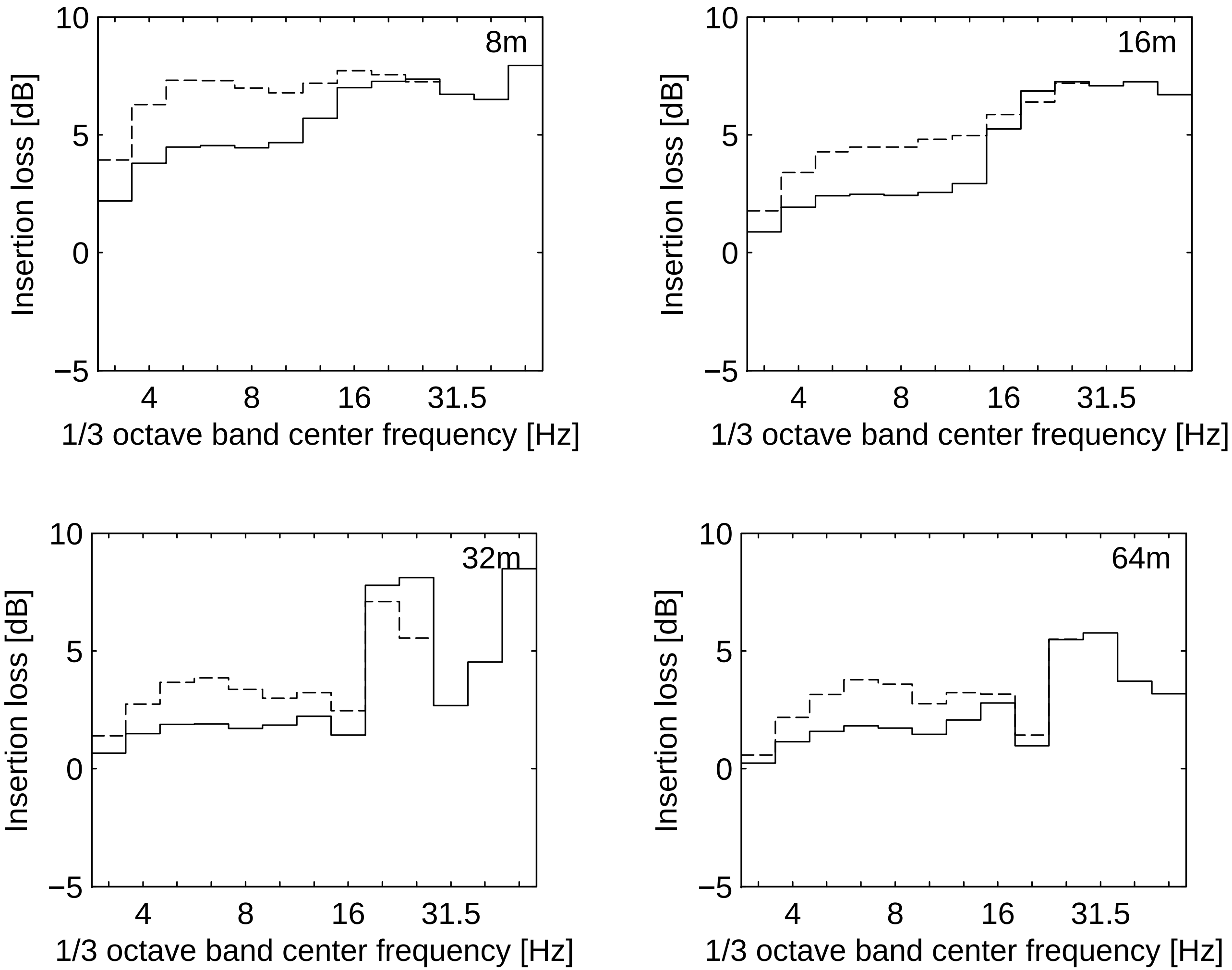


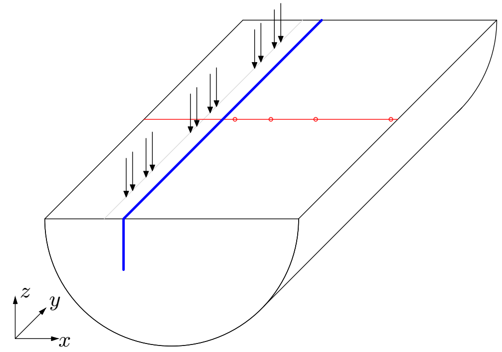




Furet test site

Vertical insertion loss for a line load





Conclusions and outlook

Conclusions

- Two phenomena contribute to the vibration reduction efficiency of a stiff wave barrier:
  - interaction between Rayleigh waves in the soil and bending waves in the barrier (jet grouting wall)
  - reflections of Rayleigh waves if the barrier depth is large compared to the Rayleigh wavelength (sheet piling wall)

Outlook

- Comparison between simulations and measurements (jet grouting wall and sheet piling wall)

- A design guide with practical recommendations (RIVAS Deliverable D4.6) will be made publicly available

Thank you for your attention

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